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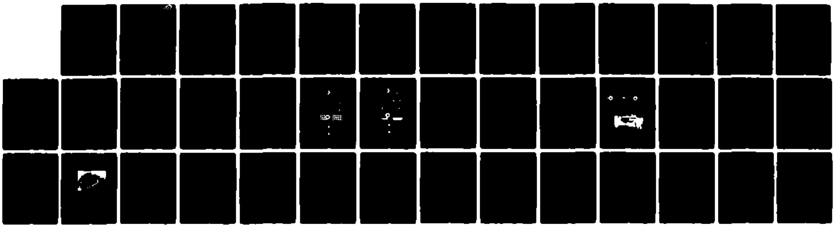

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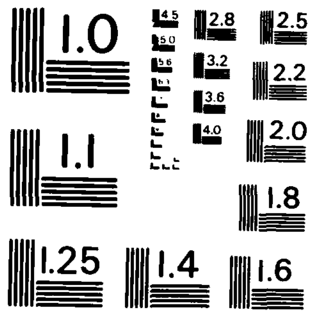

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FIRE CONTAINMENT CHARACTERISTICS OF AIRCRAFT CLASS D CARGO COMPARTMENTS

AD A131047

David R. Blake
Richard G. Hill

March 1983

Final Report

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16. Abstract

Eighteen tests were conducted in a 640-cubic foot simulated class D cargo compartment test article. Various ceiling lining materials, cargo loading configuration, air leakage rates, and fire sources were examined in a effort to determine the conditions likely to occur during a class D cargo compartment fire. The lining materials used in this project passed the requirements of FAR 25.853 and 25.855 (vertical and forty-five degree bunsen burner lab tests); however, they did not always successfully contain the cargo fires. The major conclusion of this study is that FAR 25.853 and 25.855 do not insure adequate burn-through resistance of class D cargo liners subjected to realistic fires.

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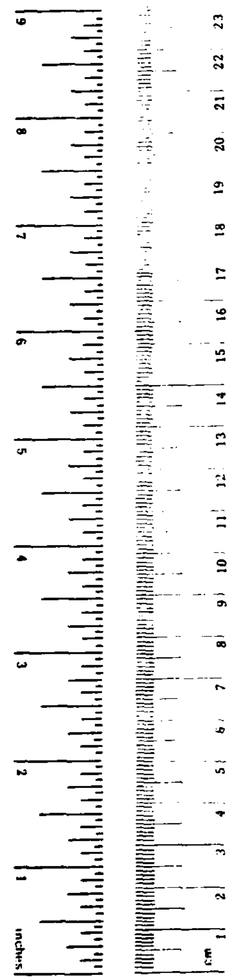
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

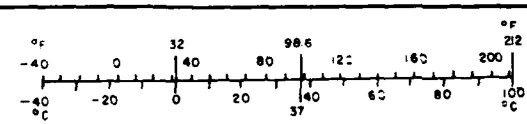
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 exactly. For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

This study resulted from the onboard fire that occurred in a Saudi Arabian airlines L-1011 in Riyadh, Saudi Arabia on August 19, 1980. The cause of the fire was unknown but was determined that it did start in the aft C3 cargo compartment. This cargo compartment is certified as class D with a volume of 700 cubic feet and is intended for the carriage of bulk cargo. Class D compartments depend on the limited availability of oxygen to contain any fire that might occur by reducing it to a smoldering state.

Eighteen tests were conducted in a 640-cubic foot simulated class D cargo compartment test article. Various ceiling lining materials, cargo loading configurations, air leakage rates, and fire sources were examined in an effort to determine the conditions likely to occur during a class D cargo compartment fire. The results of these tests in conjunction with the results of past work show that cargo fires can easily reach dangerous proportions in any size compartment. Therefore, the ceiling and sidewall lining materials must be able to withstand direct flame impingment for several minutes before oxygen starvation reduces the initial flare-up to a smoldering state, thereby containing the fire. The ceiling lining materials used in the C3 cargo compartment of the L-1011 passed the requirements of FAR 25.853 and 25.855 (vertical and 45-degree bunsen burner lab tests); however, they did not successfully contain the cargo fires in the test article. The major conclusion of this study is that FAR 25.853 and 25.855 do not reflect the burnthrough resistance of class D cargo liners subjected to realistic fires. The study also demonstrated that an effective fire barrier (e.g., fiberglass) can contain fires in a small (640 cubic foot) class D cargo compartment. It was also concluded that forced ventilation ("pet air") resulted in more rapidly growing and intense fires. Finally, the performance of the smoke detector used in the C3 compartment was examined, and the responsiveness and performance under various test fires was documented.

INTRODUCTION

PURPOSE.

The objective of this project was to experimentally study the effectiveness of transport aircraft class D cargo compartments in containing fires through oxygen starvation. Various cargo loading configurations, air leakage rates, fire sources, and ceiling lining materials were examined in a 640-cubic foot cargo compartment test article. This was done in partial fulfillment of the twofold overall objectives which were to: (1) determine the characteristics of class D cargo compartment fires, with particular attention given to the adequacy of current design practices and regulatory requirements in containing the fire, and (2) when necessary, develop design features and cargo liner test requirements which can be incorporated into improved regulations needed to safely contain likely fires in class D cargo compartments. The technical approach to this consists of three parts: (1) a data survey, (2) a mathematical analysis, and (3) an experimental effort. This report contains the results of the data survey and the initial experimental effort.

BACKGROUND.

The lower cargo compartments used in large transport aircraft fall into either class C or class D category. Class C compartments range in size from 735 to 6,200 cubic feet. They are required to have fire suppression and automatic smoke detection systems. Class D compartments are limited in size to 2,000 cubic feet. They are not required to have detection or extinguishing systems. Instead, they depend on the limited availability of oxygen to suppress any fire likely to occur. The requirements of all classes of cargo compartments are listed in appendix A.

The current policy for the certification of class D cargo compartments is that the sum of the compartment volume in cubic feet and the leakage rate in cubic feet per hour must be less than 2,000. For example, a 500-cubic foot compartment may have a maximum leakage rate of 1,500 cubic feet per hour (CFH) while the leakage rate of a 1,500 cubic foot compartment must be 500 CFH or less. The lining material used in class D cargo compartments must pass vertical and 45-degree bunsen burner tests as outlined in FAR 25.853 and 25.855.

Table 1 summarizes the cargo compartment volumes and liners for present and planned aircraft in the United States (U.S.) Fleet. The lining materials listed are the base fabrics. They are impregnated with various resins to form rigid sheets. The thickness listed is approximate for the ceiling liners. Lower sidewall liners are usually as thick or thicker than the ceiling liners. In some cases the upper sidewall liners are thinner than the ceiling liners. This depends on the intended use of the particular cargo compartment (i.e., bulk load or containerized). The majority of aircraft use fiberglass liners of various thicknesses. The two exceptions to that are the Nomex™ liner used in the L-1011 and the Kevlar™ liner planned for use in the 757 and 767. In the past, compartments under 2,000 cubic feet were designed to be class D, however, Boeing has decided to use class C compartments on their newly designed aircraft, even though the compartments on the 757 are only 735 to 1,135 cubic feet in volume.

TABLE 1. SUMMARY OF CARGO COMPARTMENT SIZES AND LINER TYPES

Model	Class	Volume Range	Liner
DC-8	D	284- 1003	Fiberglass (0.020)
DC-9	D	227- 717	Fiberglass (0.020)
DC-10	C	2445- 3045	Fiberglass (0.020)
DC-10	D	805- 1585	Fiberglass (0.020)
L-1011	D	700- 1632	Nomex™ (0.027) Fiberglass (0.034)
L-1011	C	2200- 2480	Nomex™ (0.027) Fiberglass (0.034)
B 707	D	885	Fiberglass (0.028)
B 727	D	760- 870	Fiberglass (0.020)
B 737	D	405- 550	Fiberglass (0.030)
B 747	C	2200- 6200	Fiberglass (0.020)
B 757	C	735- 1135	Kevlar™ (0.018)
B 767	C	2340- 2600	Kevlar™ (0.013- 0.020)

A major design distinction not accounted for in the classification of cargo compartments is that of bulk load versus containerized load. Bulk load compartments are those in which baggage and cargo to be shipped are loaded individually into the cargo compartment. In a containerized compartment, the baggage and cargo are first placed in a container (aluminum, fiberglass, etc.) and the containers are then loaded into the cargo compartment.

The cargo compartment liner is the initial fire barrier for the protection of aircraft components, structure, passengers, and crew from a fire initiated inside the compartment. For a class D compartment it provides for the containment of the fire within the compartment (not allowing the fire to penetrate the liner) until consumption of oxygen by the fire itself reduced the fire to a controllable smoldering state. The importance of the liner in limiting the available air for combustion is illustrated in figure 1. Because of the cabin exhaust ventilation airflow around the cargo compartment, an opening, rupture or burnthrough of any portion of the cargo liner could feed a cargo fire with large quantities of air.

In many aircraft, vital components are located between the fuselage or the cabin floor and the cargo liner, with the liner providing the only barrier from a fire in the cargo compartment. These components include electrical wiring, control cables, hydraulic lines and fuel lines. The distance between the cargo compartment liner and the passenger cabin floor, which is usually made of an aluminum faced sandwich with either a Nomex honeycomb or balsa core, is less than 1 foot.

Some cargo compartments, although primarily lined with fiberglass have aluminum components such as pressure relief vents in the ceiling or sidewall. Also noted in the inspection of some cargo compartments was the use of a removable aluminum sandwich type bulkhead divider used to separate a cargo compartment from a galley. The use of aluminum may nullify the fire containment capability of burnthrough resistant cargo compartment liners. The incidence of cargo compartment fires are infrequent but they do occur and the potential for serious damage exists. Some of the reported ignition sources of passenger luggage include kitchen matches, contact with light bulbs, and volatile liquids or chemicals. The ability of a typical

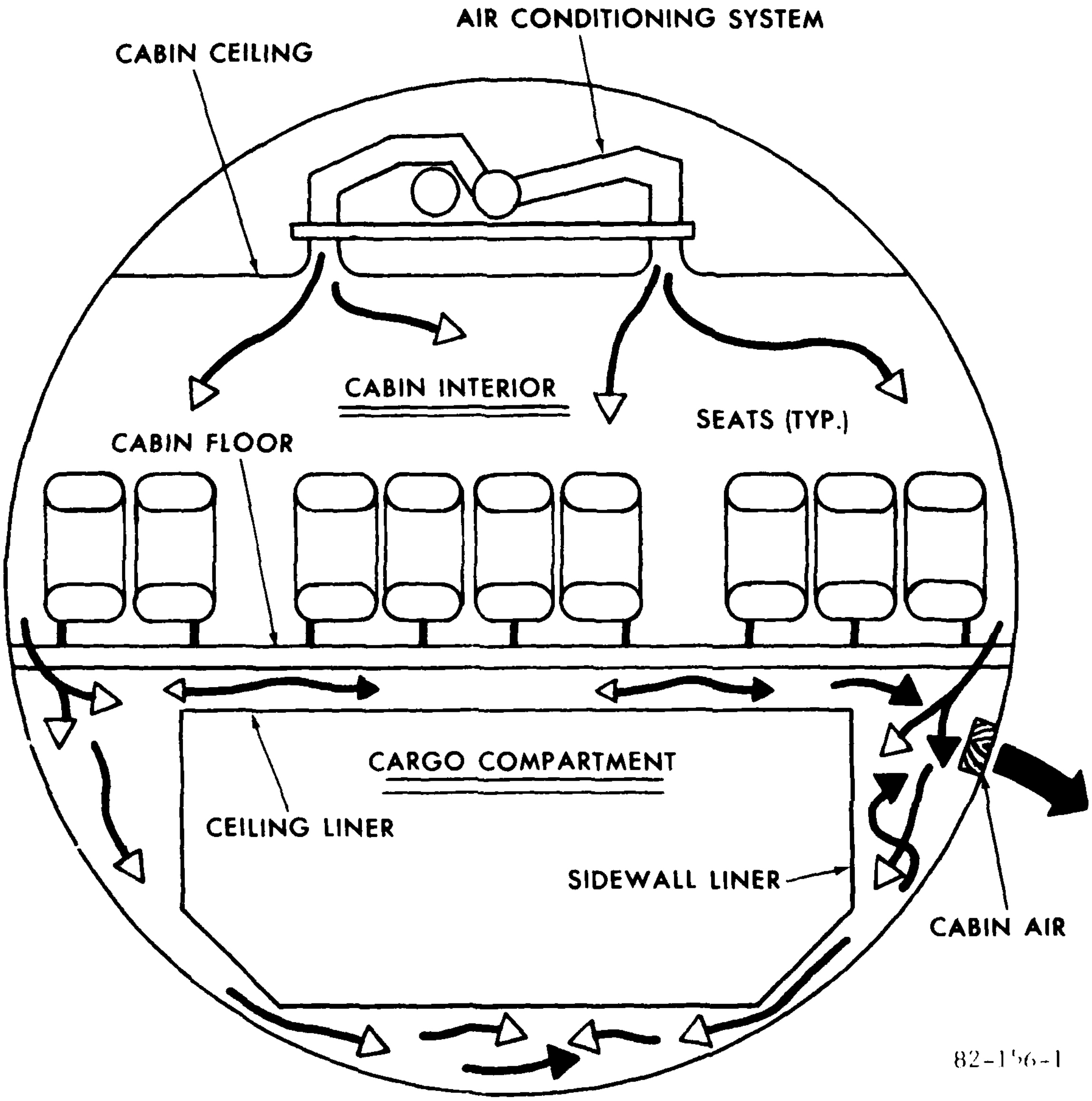

FIGURE 1. TYPICAL AIRCRAFT VENTILATION

piece of luggage to support combustion depends mainly on the initial heat output of the ignition source and the type and density of the packed clothing. Under certain conditions, a fire can smolder inside a suitcase for many hours before breaking through the suitcase wall and producing flames. Appendix B contains some examples of smoke or fire reported in cargo compartments.

The following is a description, condensed from the official Saudia Arabian Government's accident report, of the only documented example of a fatal in-flight fire originating in a cargo compartment in a large transport aircraft.

On August 19, 1980, Saudi Arabian Airlines Flight 163, a Lockheed L-1011 Tristar, departed Karachi, Pakistan. It was bound for Jeddah, Saudi Arabia with a scheduled stop in Riyadh, Saudi Arabia. The aircraft landed at Riyadh at about 1606 after an uneventful flight from Karachi. All luggage, both carry-on and that stored in the cargo compartments, was unloaded at Riyadh to be cleared through customs. Passengers and baggage were reloaded and after refueling, the plane departed the gate at 1750. At 1814:54, 6 minutes and 54 seconds after takeoff, both visual and aural warnings signaled the presence of smoke in the AFT cargo compartment. The flight crew spent the next 4 minutes and 21 seconds confirming those warning signals and then decided to return to Riyadh. The first officer notified the tower at Riyadh that they had an onboard fire and were returning. The aircraft landed at Riyadh at 1836:24. It made a normal landing rollout and then turned off the end of the runway onto a taxiway. It came to a stop 2 minutes and 40 seconds after touchdown.

For unknown reasons, the captain did not shut down the engines immediately after landing and there was no apparent attempt to evacuate the plane. At some point prior to stopping the airplane, the ventilation system was turned off and most of the overboard valves were closed. Approximately 3 minutes after the plane stopped the engines were shut down. This was almost immediately followed by a "big puff of white and black smoke emitted from the aircraft belly just forward of the wings" (reference 3). This was the result of a flash fire that spread through the cabin. Twenty-three minutes passed after the engines were shut down before the crash fire and rescue crew were able to open a door in the plane. Firefighters called into the cabin but received no response. After another 3 minutes the cabin was completely engulfed in flames. All 301 people onboard died in the fire. The cause of the fire was unknown but it was determined to have originated in the C3 cargo compartment. It burned through a portion of the compartment sidewall and ceiling liner and cabin flooring and spread through the cabin. The C3 cargo compartment is 700 cubic feet and is classified as a class D compartment. Although class D compartments are not normally required to have smoke detectors, the C3 compartment was equipped with two detectors. The allowable air leakage rate for this size compartment is 1,300 cubic feet per hour. The C3 compartment normally exceeds this rate with forced ventilation system to allow for the transport of pets. This forced ventilation shuts down automatically when smoke is detected to lower the leakage to the allowable limit. However, it is believed that the supplemental airflow system was inoperative during the final flight, and therefore was not considered a factor in the development of the fire.

PREVIOUS CARGO COMPARTMENT RESEARCH.

One of the first test programs concerning fire protection was conducted by L. A. Asadourian (reference 2). This work was the basis for the present class D requirements. It should be noted that the largest volume tested was 270 cubic feet, with most of the tests being conducted in a 110-cubic foot test article. Table 2 shows

that even for tightly sealed small compartments, open flaming can last for a few minutes. Also shown is that small amounts of air entrainment into a compartment can allow the fire to burn continuously.

TABLE 2. EFFECT OF AIR-LEAKAGE RATE ON OPEN-TYPE BAGGAGE FIRES (REF. 2)

Test Series	Compartment Volume Cu. Ft.	Leakage Rate Cu. Ft/Hr	Open Flame			Time for Flame Suppression (min.)
			Suppressed	Intermittent	Continuous	
1	48	0	X			1
2	110	0	X			2 1/2
3	270	0	X			1 1/2
4	48	1500	X			2
5	110	1500	X			3
6	110	1500	X			2 1/2
7	110	1500	X			3
8	110	1500		X		
9	48	1680		X		
10	48	1900			X	
11	48	1900			X	
12	110	1900			X	
13	110	2100			X	
14	110	3600			X	
15	110	3600			X	

Some of Asadourians conclusions were:

1. A completely sealed compartment will prevent any large or dangerous flame from existing for more than a few minutes.

2. The volume of a compartment, with no leakage, directly affects the time required to reduce the open fire to a smoldering condition.

3. The quantity of air injected into a compartment, regardless of the compartment size, determines the maximum size of the fire that can continue to burn.

4. Class A fires in a smoldering condition (not producing visible flame) can burn for an indefinite period of time, even if the leakage rate approaches zero.

Relative to present class D compartments, these conclusions indicate (1) Large and dangerous flames can exist in completely sealed cargo compartments of a small volume (48 to 270 cubic feet) for a few minutes; (2) As the volume of the compartment increased, the time of open flaming also increases; (3) Whether the fire can be reduced to a smoldering condition by oxygen consumption in the compartment is dependent on the lining materials ability to limit the airflow into the compartment; and (4) Baggage fires will probably not be fully extinguished in any class D compartment. A class D compartment is designed to reduce open flaming to a smoldering state. Entrainment of oxygen into the compartment at a later point in time will again cause open flaming.

In the mid 1960's, the Federal Aviation Administration (FAA) began a program concerning larger cargo compartment fire protection. Gassmann, in references 3 and 4, conducted tests in volumes up to 5,000 cubic feet. In reference 3, based on tests in 5,000 cubic-foot volumes only, it was concluded that:

1. Fires in large cargo compartments involving currently used packaging materials can readily reach damaging proportions even though detection and airflow shutoff occur immediately.

2. In order to protect the structure of a large compartment containing a small amount of cargo from fire damage utilizing ventilation shutoff, a well designed interior insulation system must be provided, with particular attention given to the thermal insulating adequacy of the belt frames and to the types of fastenings used.

Figures 2 and 3 are from reference 4 and show the effect of volume on fire severity. In terms of maximum fire severity, a 2,000 cubic-foot compartment was the same as a 5,000- cubic foot compartment. This leads to the deduction that the conclusions stated from reference 3 are also valid for compartments of 2,000 cubic feet. Figure 3 shows that relatively high temperatures can be reached even in compartments as small as 500 cubic feet.

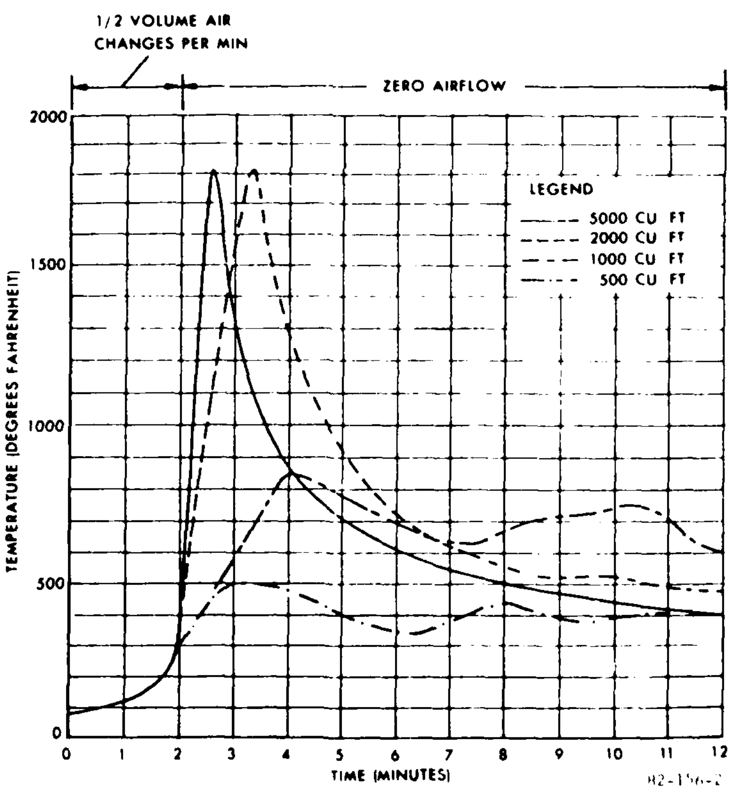

FIGURE 2. TEMPERATURE VERSUS TIME FOR VARIOUS SIZE COMPARTMENTS (REFERENCE 4)

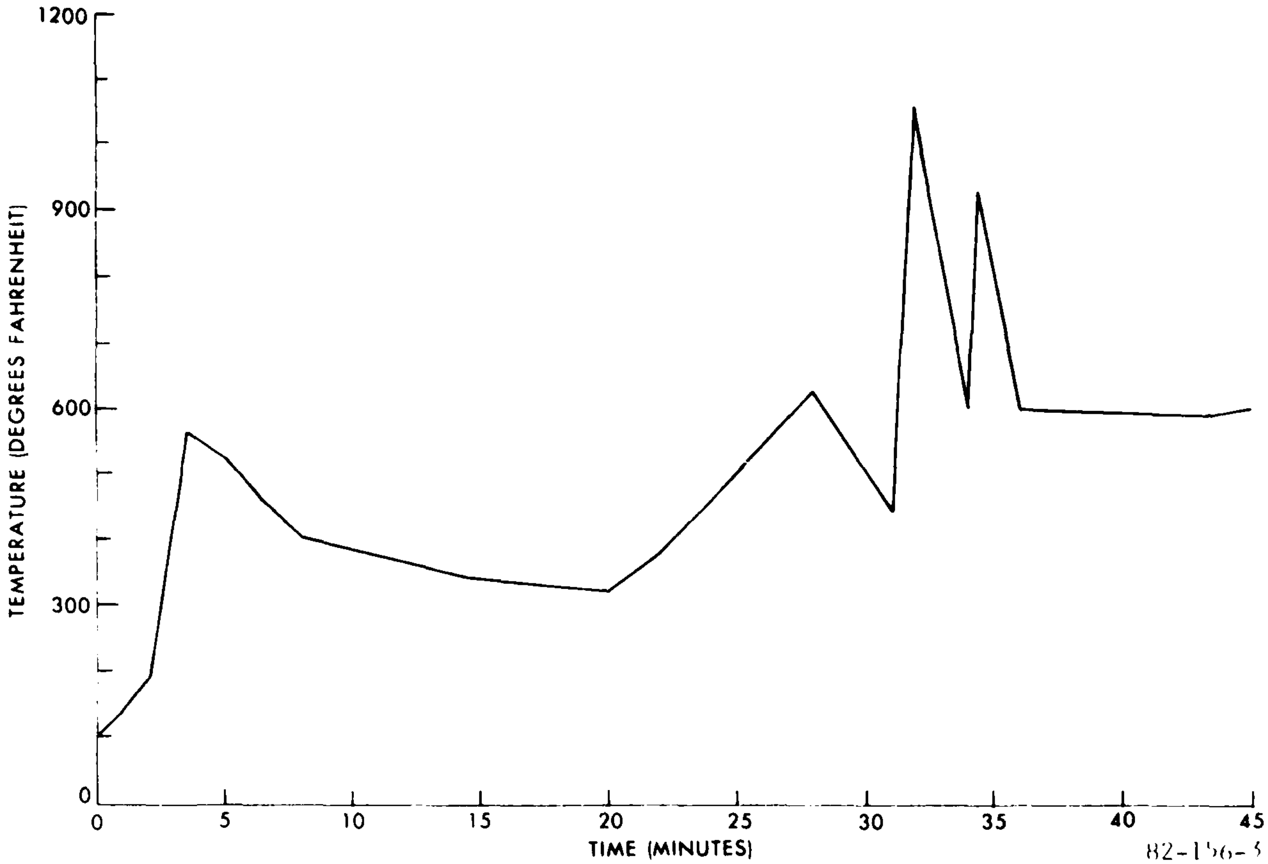

FIGURE 3. TEMPERATURE VERSUS TIME FOR 500 CUBIC FOOT COMPARTMENT (REFERENCE 4)

In 1976 work was completed by Lockheed-California company on a study for improving fire safety on transport aircraft (reference 5). Table 3 reproduces their summary findings with regards to cargo compartments. Based on improved fire safety, ceiling and sidewall liners constructed of fiberglass impregnated with a high temperature resin (phenolic) were recommended for consideration.

Two full-scale cargo compartment tests were conducted by McDonnell Douglas Corporation and reported in 1977 (reference 6). The tests used a 2,000-cubic foot volume compartment and fiberglass/epoxy cargo liners. The following conclusions were reached from those tests:

"Fire protection systems and airflow shutoff procedures such as on present day aircraft and/or more fire resistant ceiling liners than epoxy fiberglass are essential for containment."

TABLE 3. ZONE MATERIAL BREAKDOWN-CARGO COMPARTMENTS (REFERENCE 5)

ASSEMBLY	TYPE NON-METALLIC MATERIAL	EXPOSED AREA (ft^2)	WEIGHT (lbs)	POSSIBLE ALTERNATE MATERIAL CONSIDERATIONS OR REQUIREMENTS
Ceilings	Polyester/glass or Nomex laminate. Phenolic/glass laminate	1000	200	Phenolic/glass laminate
Sidewalls	Epoxy/Nomex fabric	2000	500	Same as ceiling
Floors	Aluminum Sheet Titanium/crushed Aluminum core sandwich Epoxy/aluminum/Nomex laminate	- -	- -	No change
Injection molded plastic parts, (Light frames). Air grilles	Polycarbonate	18	10	Modified polycarbonate or polyphenylene sulfide.
Aft cargo tie-down straps	Polyamide	- -	- -	No change recommended

The latest reported cargo compartment tests results are in reference 1 (the official aircraft accident report of the Saudi Arabian Airlines L-1011 in Riyadh, Saudi Arabia in August 1980). Tests by Lockheed revealed "that a 1300° F 6-inch diameter butane flame will penetrate the ceiling liner of 0.030 inch Nomex in 43 seconds and a 1500° F similar flame will penetrate it in 36 seconds."

The above analysis of past research findings and implications of past cargo compartment fires, particularly the Saudi Arabian Airlines L-1011, indicate the need for an examination of the adequacy of current design practices and requirements for class D cargo compartment fire protection. This report describes test results and findings obtained in a 640 cubic foot class D cargo compartment test article under various cargo load configurations, air leakage rates, fire sources and ceiling lining materials.

DISCUSSION

TEST ARTICLE.

The test article was a converted school bus with a bulkhead across the front section, giving a usable interior volume of 640 cubic feet. A drop ceiling framework was installed and cargo compartment liners were tested in the middle third of the ceiling; sheet metal was installed on the ends. A fan capable of delivering up to 200 cubic feet per minute was placed through the forward bulkhead. An electric valve was installed on the front of the fan and both could be operated from the control room. This setup simulated the forced ventilation system used in some class D cargo compartments for animal carrying capabilities. The valve could be closed and the fan shut off if a smoke detector signaled the presence of smoke in

the compartment. Makeup air entered through natural leakage points in the test article. Another fan was mounted on the front of the bus above the drop ceiling. It was used to draw air across the top of the ceiling liner through an opening in the rear of the bus and out the front. This simulated the path of cabin air around the cargo compartment that was exhausted overboard. This fan was used in all tests and was calibrated at 260 cubic feet per minute.

INSTRUMENTATION.

Twenty-three chromel-alumel thermocouples were used in the test article. A thermocouple tree was placed near the back to measure the stratification of temperature. Starting from the ceiling, the thermocouples were placed at 9-inch intervals. Twelve thermocouples were installed in the middle third of the ceiling. Six below and six above. The above-ceiling thermocouples were used to determine the time of burnthrough, if it occurred. In addition, there was a closely spaced grid of five thermocouples installed directly above the fire origin to determine the peak temperatures on the ceiling liner. This configuration of thermocouples was used in tests 2 through 10. Three closely spaced grids of six thermocouples each were used for the remaining tests. They were installed adjacent to a fire pan placed against the side of the test article. One on the ceiling directly over the pan, one on the upper sidewall and one in the middle of the sidewall. These grids were used to better resolve the temperature profiles on the ceiling and sidewall.

Four calorimeters were installed at various locations to measure the incident heat flux on ceiling and sidewall liners. One was placed directly above the fire origin to measure the greatest heat flux the liner would be exposed to with the type of fire simulated.

A smokemeter was installed at ceiling level on the forward edge of the section of ceiling where the lining material was attached. It consisted of a collimated light beam incident on a photocell placed 1 meter away.

Aircraft quality photoelectric type smoke detectors were used in this project. They consist of a light source and a small photocell inside a vented chamber. The light does not strike the photocell under clear conditions. When smoke enters the chamber the particles scatter the light beam and some light strikes the photocell. When the photocell output reaches a certain level corresponding to a light reduction of 4 to 6 percent over 1 foot, it activates the alarm circuit. Cargo compartment smoke detectors are required to alarm when the light transmission over 1-foot is reduced between 4 to 16 percent. The smoke detector alarm output was used to activate lights on the control panel to signal the presence of smoke. One detector was a recessed ceiling type, mounted in the front right corner of the test article. This was the detector used to determine when the compartment ventilation would be shut off. The other detector used was a flow through type mounted on the outside of the bus. Air was drawn from a point on the ceiling just forward of the smokemeter, through the detector, and then returned to the inside of the test article.

The oxygen concentration inside the test article was monitored using a Beckman OM-11 oxygen analyzer. The sampling point was on the sidewall 1-foot below ceiling level and just aft of the lining material. Ambient air was assumed to contain 21 percent oxygen.

The tests were visually recorded using two black and white video cameras looking through the forward bulkhead. One camera viewed the actual fire in the compartment

and the other was mounted above the ceiling to monitor liner burnthrough. In addition, a low light level, 16-millimeter color camera recorded the fire through the forward bulkhead. Thrity-five millimeter photographs were taken before and after most tests.

All data channels were fed through an analog-to-digital converter and stored on the fixed disk of a Data General mini computer. The millivolt data were later converted to engineering units and automatically plotted.

TEST SERIES.

A total of 10 tests was conducted using unclaimed luggage as the fire load. This was stacked in the center of the test article. Cardboard boxes were used to fill the remaining space to achieve a 50 percent load by volume. The fire was started in a plastic gym bag filled with rags, newspaper and two packs of book matches. These bags were placed on top of the luggage, approximately 1.5 feet below the ceiling liner. Ignition was achieved by arcing a spark from a pair of electrodes across the book matches. The fire spread to the other luggage and in some cases, the cardboard boxes surrounding the luggage became involved. For some tests, air was forced into the compartment at the rate of 130 cubic feet per minute until the time of smoke detection. In other tests the ventilation was limited to natural leakage.

Three materials were used to line the ceiling of the test article. Two of these were aircraft cargo compartment ceiling liners; (1) Nomex™, 0.027 inches thick with a unit weight of 26.5 ounces per square yard; and (2) fiberglass, 0.034 inches thick with a unit weight of 47 ounces per square yard. Galvanized steel was used in those tests designed to contain the fire within the compartment. Figure 4 shows the instrumentation used for the first series of tests.

Two tests were conducted using one liter of JP4 as the fuel in an 18-inch-square pan placed against the side of the test article and 30 inches off the floor. The purpose of these tests was to better resolve the temperature profile on the ceiling and sidewall using a controlled and predictable fire source. Figure 5 shows the instrumentation used for these and all remaining tests.

Four tests were run with a single cloth suitcase as the fire load. It was filled with rags, newspaper, and two boxes of large kitchen matches. Nichrome wire was wrapped around the tip of the matches and a current passed through it to achieve ignition. These tests were conducted in an effort to determine the conditions needed to start a fire in a cargo compartment in this manner. Testing was completed with two tests using a polyurethane seat cushion as the fire load. These cushions were ignited in the fuel pan described above to determine the ceiling and sidewall exposure conditions produced by a class A fire with a rapid burning rate. Table 4 summarizes the tests conducted listing the ventilation rate, liner type, fire load, and general comments.

ANALYSIS OF RESULTS.

The first ten tests simulated a fire in a fully loaded class D bulk load cargo compartment. The method of ignition used was an attempt to simulate a realistic and reliable ignition source. An attempt was made to eliminate test variability by starting the fire the same way each time. However, growth of the test fire did vary from one test to another. This was partly due to test variables such as

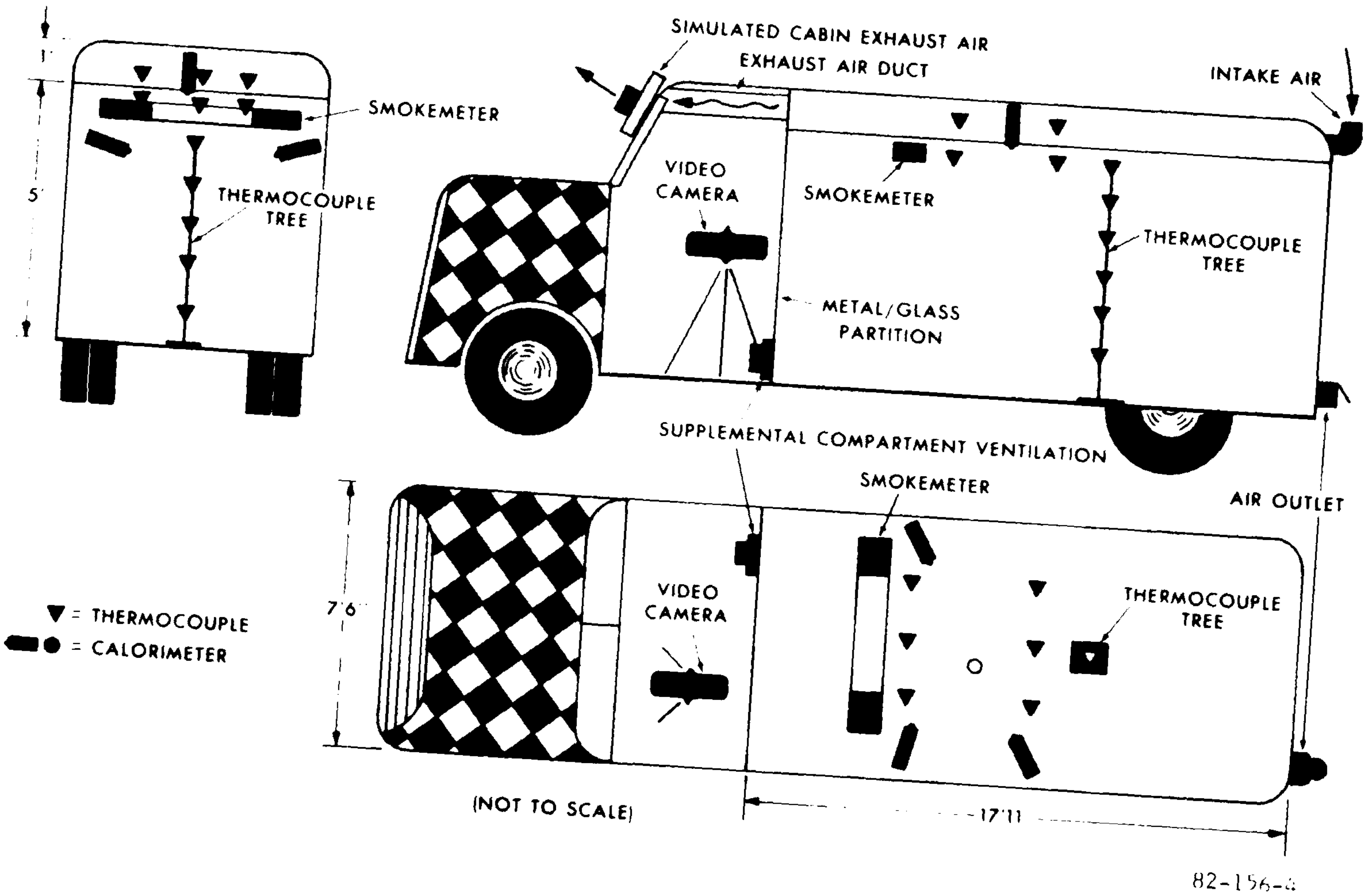

FIGURE 4. TEST ARTICLE INSTRUMENTATION, TEST 2 THROUGH 1?

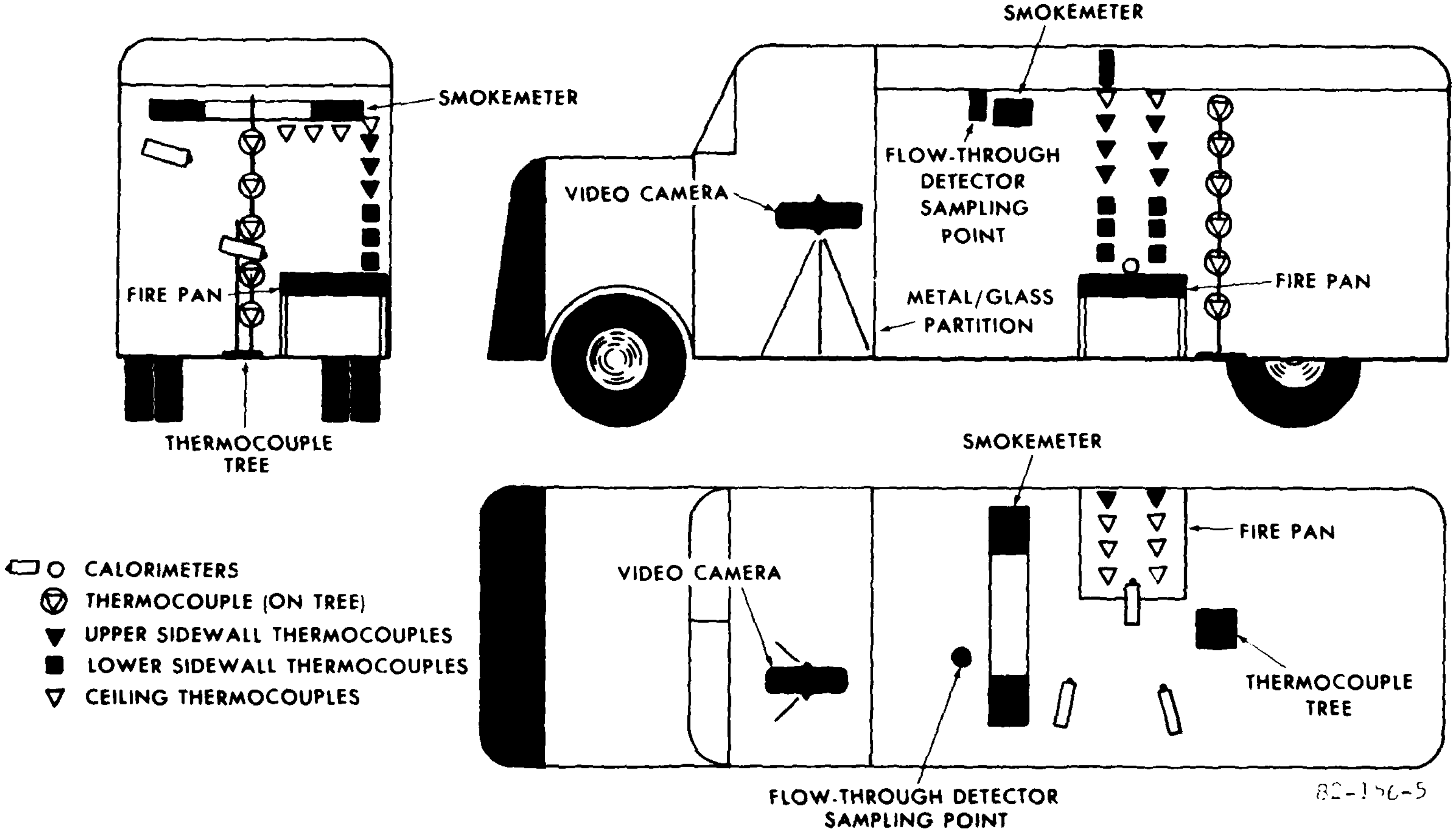

FIGURE 5. TEST ARTICLE INSTRUMENTATION, TEST 11 THROUGH 18

TABLE 4. SUMMARY OF TESTS

Test Number	Airflow Before Detection	Airflow After Detection	Liner	Fire Load	Comments
1	130 CFM	No Detection	NOMEX™	Canvas Bag 50% load	Bag smoldered for two minutes and then self extinguished.
2	130	0	NOMEX™	Canvas Bag 50% load	Liner burn through occured 10 seconds after smoke detection.
3	0	0	NOMEX™	Plastic gym bag 50% load	Liner burn through occured about 30 sec. after smoke detection.
4	130	0	Metal	Plastic gym bag 50% load	Peak temperature of 1100° F. One smoke detector destroyed in fire.
5	0	0	Metal	Plastic gym bag 50% load	Very little smoke. Fire burned slowly and did not spread.
6	130	0	Metal	Plastic gym bag 50% load	Fire burned slowly and did not spread. No airflow above ceiling.
7	130	0	Fiber-glass	Plastic gym bag 50% load	Peak temperature on 1560° F. Fire did not penetrate liner.
8	0	0	Fiber-glass	Plastic gym bag 50% load	Fire started slowly. Did not penetrate liner.
9	0	0	Fiber-glass	Plastic gym bag 50% load	Flow thru detector went on and off several times remained on after 8 mins. Did not penetrate liner.
10	130	0	NOMEX™	Plastic gym bag 50% load	Fire burnt through liner at approximately 8 mins. Recessed detector went out at 15 minutes.

TABLE 4. SUMMARY OF TESTS (Continued)

Test Number	Airflow Before Detection	Airflow After Detection	Liner	Fire Load	Comments
11	0	0	Metal	1 Liter JP4 no cargo	Peak temperature on ceiling was 1600° F. Occuring 1 min. after ignition.
12	0	0	Metal	1 Liter JP4 no cargo	Same results as test 11.
13	0	No Detection	Metal	One cloth suitcase	Matches were ignited in suitcase. Clothes self-extinguished.
14	0	No Detection	Metal	One cloth suitcase	Matches ignited inside suitcase. Smoldered for 15 minutes.
15	0	0	Metal	One cloth suitcase	Matches ignited inside suitcase. Dense smoke but no visible flame.
16	130	0	Metal	One cloth suitcase	Matches ignited inside suitcase. Entire case was consumed.
17	0	0	Metal	One Polyurethane cushion	Cushion was consumed in 4 minutes. 1200° F on sidewall.
18	0	0	Metal	One Polyurethane cushion	Smoke detector blinked on and off several times.

leakage rate and liner type. Other variables that affected the fire growth and intensity were: the type of luggage burning, the humidity, the type and density of the packed clothing and the configuration of the fire load. Figure 6 shows a typical fire load.

CEILING LINER BURNTHROUGH RESISTANCE.

Four tests were conducted with Nomex™ ceiling liners. For reasons unrelated to the study, no fire resulted in the first test. The fire penetrated the Nomex™ ceiling liner in the remaining three tests. Burnthrough occurred zero to forty seconds after smoke detector activation. Figure 7 shows the damage to the Nomex™ liner after test 2. The fire intensity cycled noticeably in tests 2 and 10. As the oxygen was consumed the fire subsided, allowing the oxygen level to rise again due to entrained air. When it reached a critical level, rapid burning of the combustible material resumed. Overpressurization of the compartment resulted from this rapid burning and forced smoke back against the flow of above-ceiling air and out the inlet. In an aircraft this would be analogous to smoke being forced into the pressurized cabin instead of out the overboard vents. This occurred three or four times during tests 2 and 10 (figure 7).

Three tests were conducted using a fiberglass ceiling liner. Cargo compartment temperatures similar to the tests with the Nomex liner resulted, but the fire never burned through the fiberglass liner. However, large quantities of smoke were present above the ceiling. Some of the reasons for smoke collecting above the ceiling were: the burning of the resin on the backface of the fiberglass, the permeable nature of the fiberglass cloth after the resin burned away, and the natural leakage through cracks and joints in the drop ceiling structure. There was no evidence of the cycling of the fire observed in tests 2 and 10. It should be noted that both the Nomex and the fiberglass easily passed the vertical and 45-degree bunsen burner tests required for class D cargo compartment liners. Figures 8 and 9 illustrate the effectiveness of the two different lining materials as a fire barrier. Temperatures above the ceiling liner are compared with those below the liner. Although the below-ceiling temperatures were similar, the temperature above the fiberglass liner never exceeded 400° F, while the temperature above the Nomex liner reached 1150° F. At approximately 800 seconds into the Nomex test, the above ceiling temperature exceeded the temperature below the liner. The Nomex liner no longer existed at this point. Figure 10 is a plot of oxygen concentration versus time for tests 7 and 10. The fiberglass liner was able to maintain an oxygen concentration of less than 10 percent for 10 minutes. While this did not extinguish the fire, it did reduce the initial flare up, resulting in a small fire with very little spread. The oxygen concentration during the Nomex test dropped to a minimum concentration of 10 percent but rose again to 18 percent as the liner burned away and fresh air was entrained.

EFFECTS OF VENTILATION.

Figures 11 and 12 show the effect of forced ventilation on fire growth and intensity. The temperature below the ceiling increased earlier and became hotter with both liner types when forced ventilation was used. The most severe fire in terms of above-ceiling temperatures was during test 10 using the Nomex ceiling liner and forced ventilation. Temperatures above the ceiling increased earliest in the test using the fiberglass ceiling liners and forced ventilation but the temperature leveled off before reaching 400° F. The fire in the test using the Nomex liner and no forced ventilation took longer to develop, but eventually reached

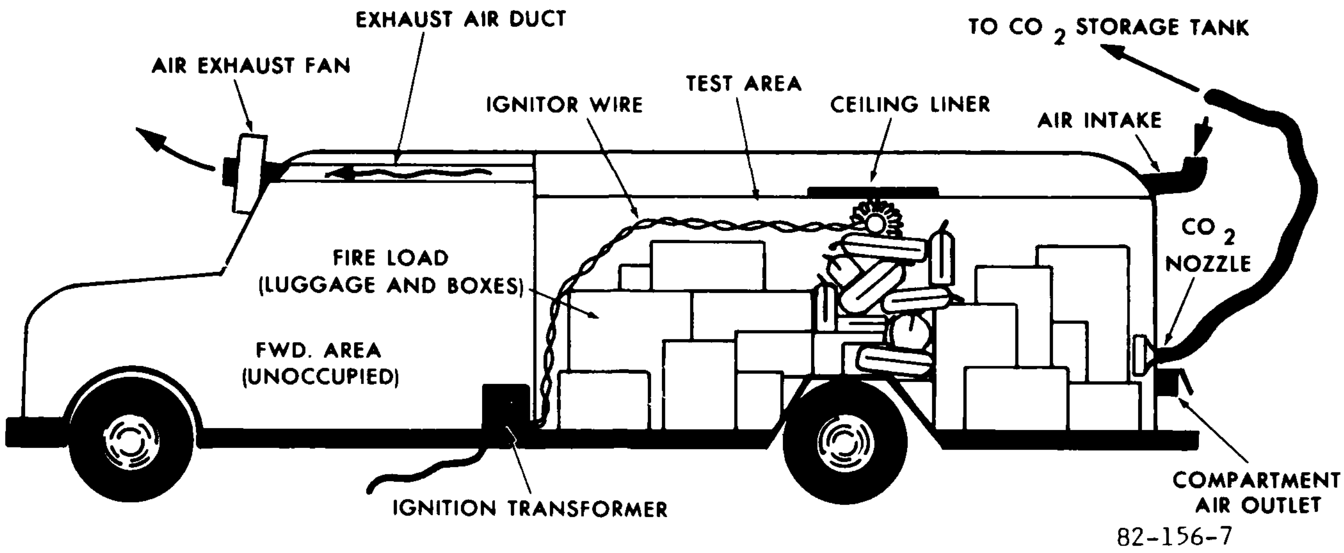

FIGURE 6. SIDEVIEW OF TYPICAL FIRE LOAD

FIGURE 7. NOMEX™ LINER AFTER FIRE TEST

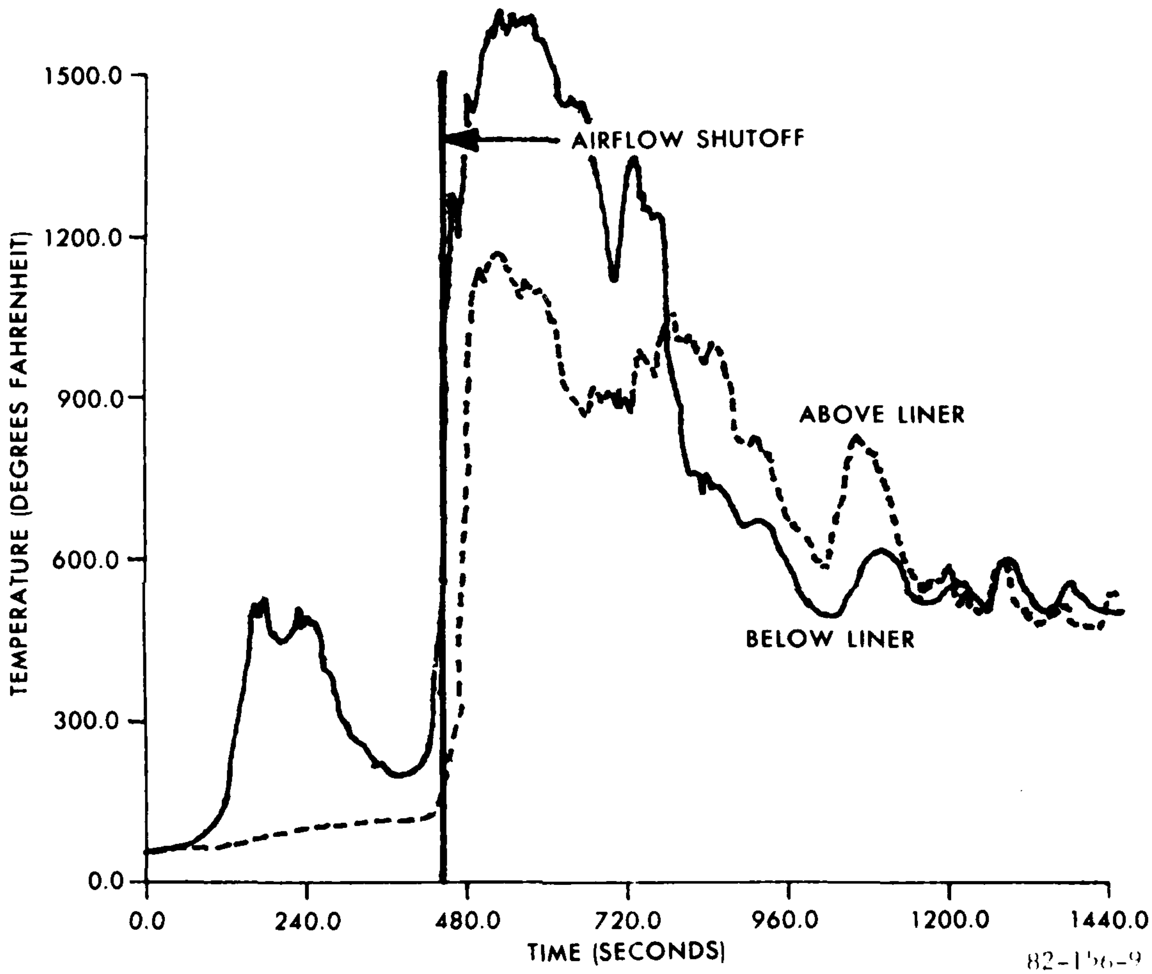

FIGURE 8. TEMPERATURE ABOVE AND BELOW NOMEX™ LINER

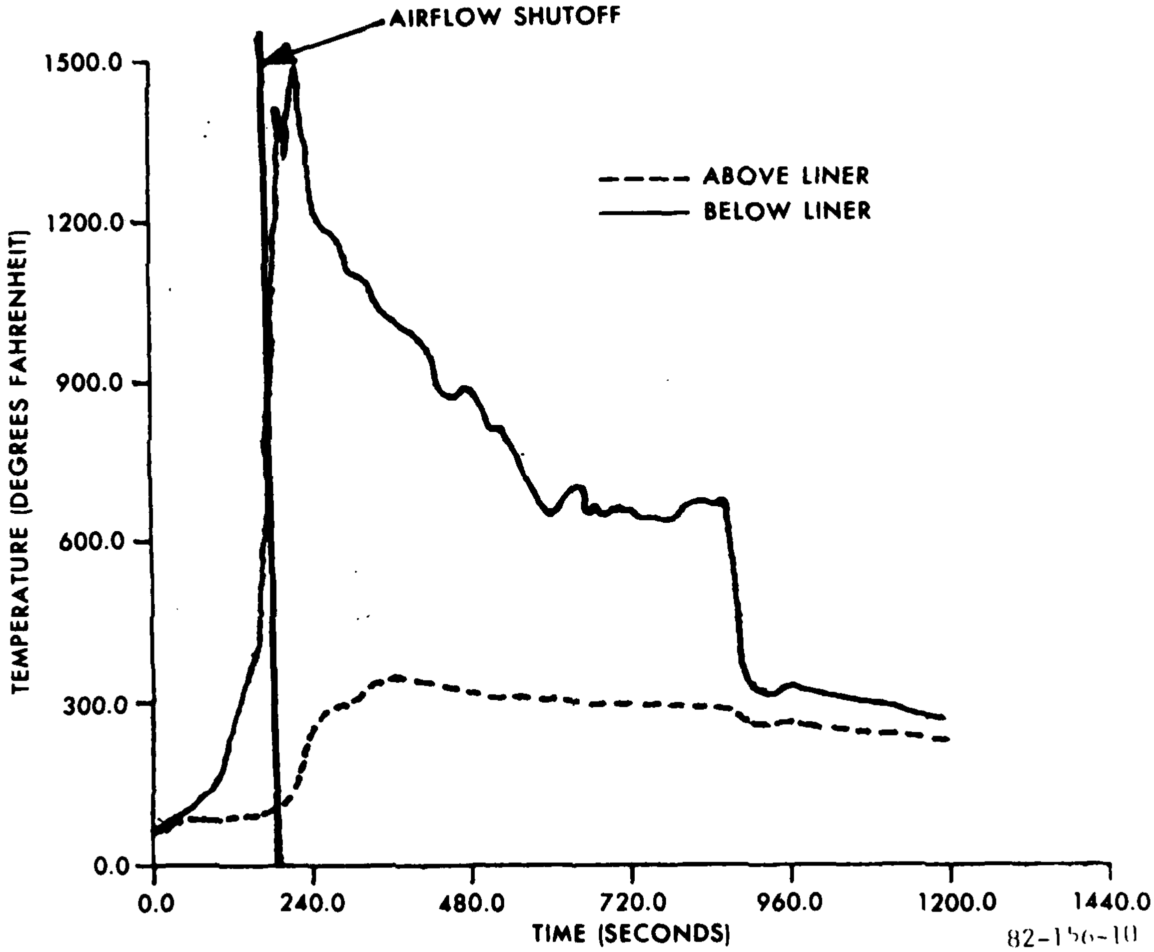

FIGURE 9. TEMPERATURE ABOVE AND BELOW FIBERGLASS LINER

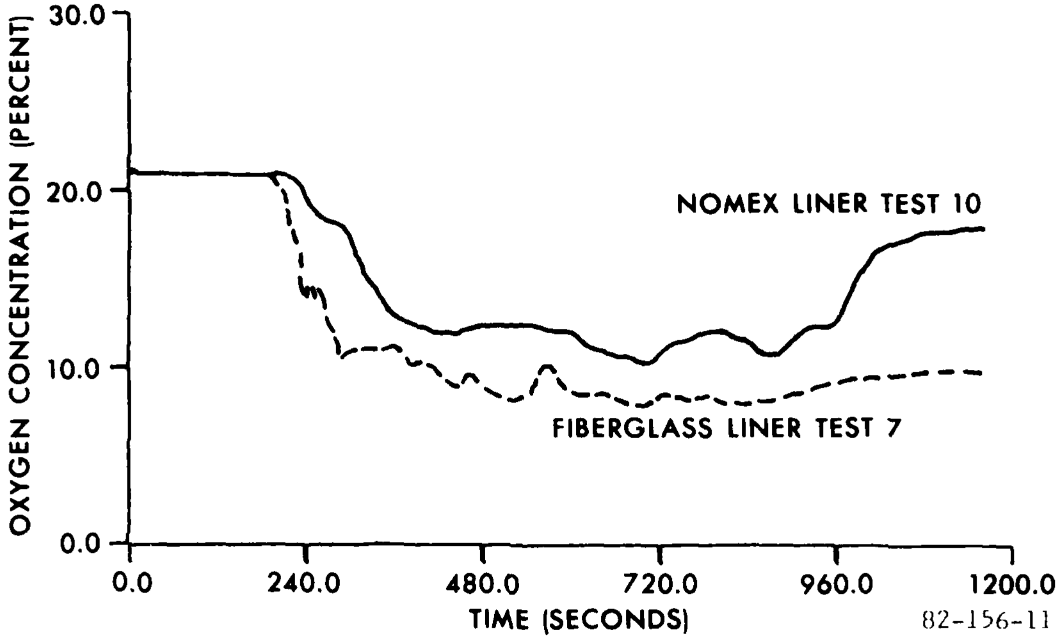

FIGURE 10. OXYGEN CONCENTRATION WITH NOMEX™ AND FIBERGLASS LINERS

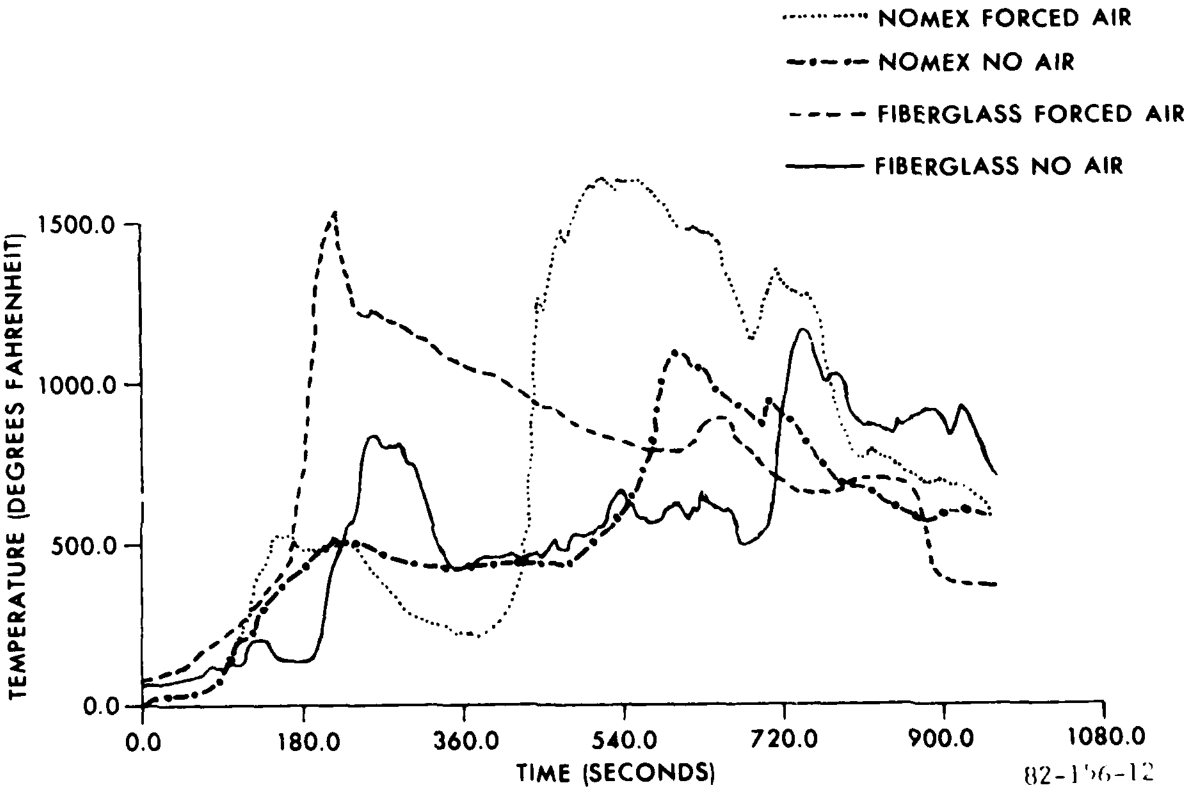

FIGURE 11. BELOW CEILING TEMPERATURES

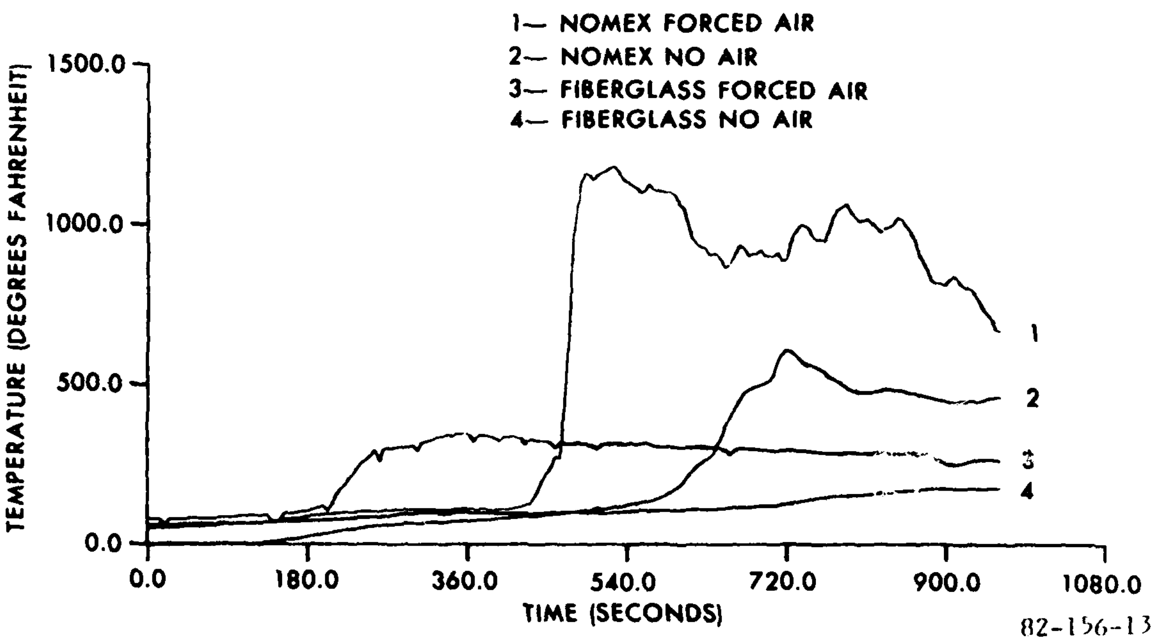

FIGURE 12. ABOVE CEILING TEMPERATURES

700° F above the ceiling as the liner burned away. In test 9, using the fiberglass ceiling liner and without forced ventilation, the temperature above the liner never exceeded 200° F.

Only one of the four tests conducted with a cloth suitcase resulted in a fire, which consumed the entire case. This was the only test of the single suitcase where forced ventilation was used. Figure 13 shows the scorched clothing after test 15. The clothes in this test self-extinguished after approximately 25 minutes.

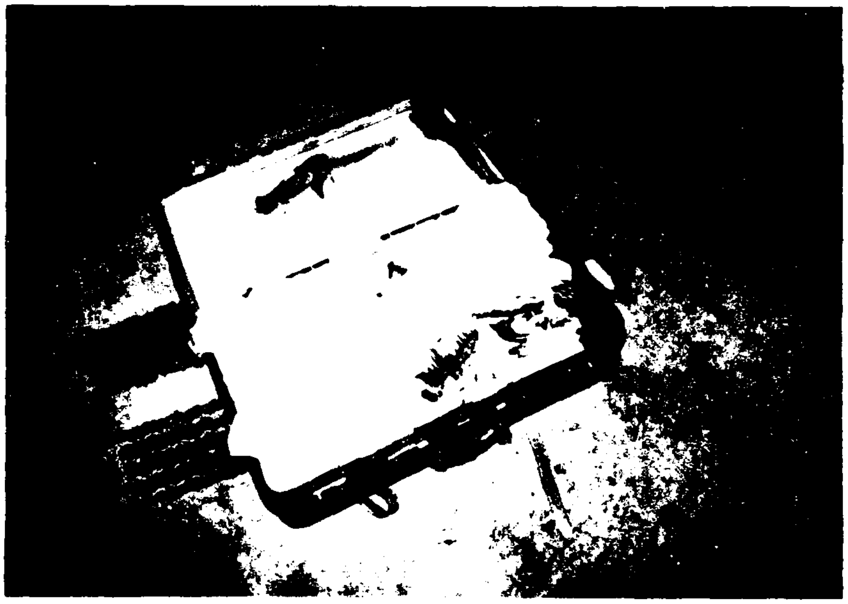

FIGURE 13. SCORCHED CLOTHING AFTER TEST 15

Forced ventilation, in some cases, produded a flaming condition leading to a self-sustaining fire, whereas without ventilation a fire may be limited to a smoldering condition and self-extinguishment.

FIRE EXPOSURE CONDITIONS.

The maximum temperature measured by the ceiling thermocouples was in test 10 and was approximately 1700° F. Maximum ceiling temperatures recorded in other tests where the fire developed beyond the initial flare-up were in the range of 1500 to 1700° F. Sidewall temperatures were slightly less. Figure 14 is a plot of the temperature on the ceiling and sidewall resulting from igniting one liter of JP4 in a fire pan. Similar temperatures were recorded when polyurethane seat cushions were ignited in this same pan. Temperatures in 2000- and 5000-cubic foot compartments reached 1800° F as seen in figure 2.

Maximum heat flux levels recorded on the ceiling were in the range of 6.0 to 8.6 BTU/ft^2-second for the tests that developed beyond a smoldering condition. Figure 15 shows the heat flux incident on the ceiling liner for test 7 and 10 using fiberglass and Nomex ceiling liners, respectively.

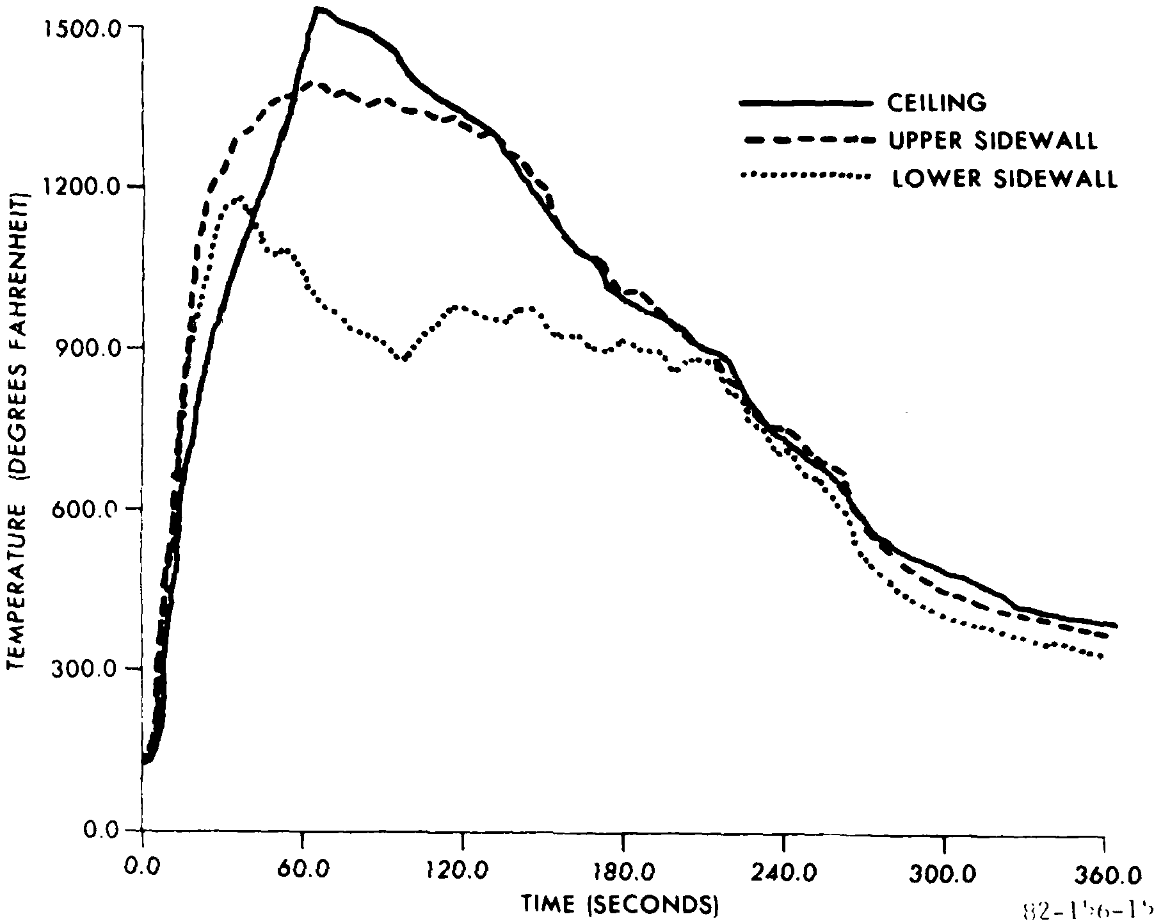

FIGURE 14. TEMPERATURE PROFILE WITH JP4 AS A FIRE SOURCE

SMOKE DETECTION.

The smoke detectors did not consistently alarm at the same level of smoke obscuration. The percent light transmission over 1 foot, as measured by the smoke meter, ranged from 77.6 to 94.4 at the time the ceiling detector alarmed. The flow-through detector alarmed between 90.4 and 98.3 percent light transmission. These levels of light transmission were at the location of the smokemeter, the light transmission at the smoke detectors may have been different. The sampling point for the flow through detector was closer to both the smokemeter and the fire origin than the recessed detector. The proximity to the fire origin contributed to the faster response time of the flow-through detector. The recessed ceiling detector became saturated on several occasions. The smoke in the detector's chamber apparently became so dense that no reflected light could reach the photocell. This caused the light on the control panel to go out, indicating no smoke in the compartment. However, there is a test lamp in the detector chamber directly across from the photocell that can be lit from the control panel to check the functioning of the detector. Although the flow-through detector responded faster in almost every case, its signaling was more erratic than the recessed detector. No false

warnings were observed with the flow-through detector but the light on the control panel blinked off and on several times during some tests when there was heavy smoke in the test article. This detector did not appear to become saturated and except for the blinking, remained on until CO_2 was discharged into the test article. Table 5 shows the time of detection for the two smoke detectors and the percent light transmission at those times as measured by the smokemeter.

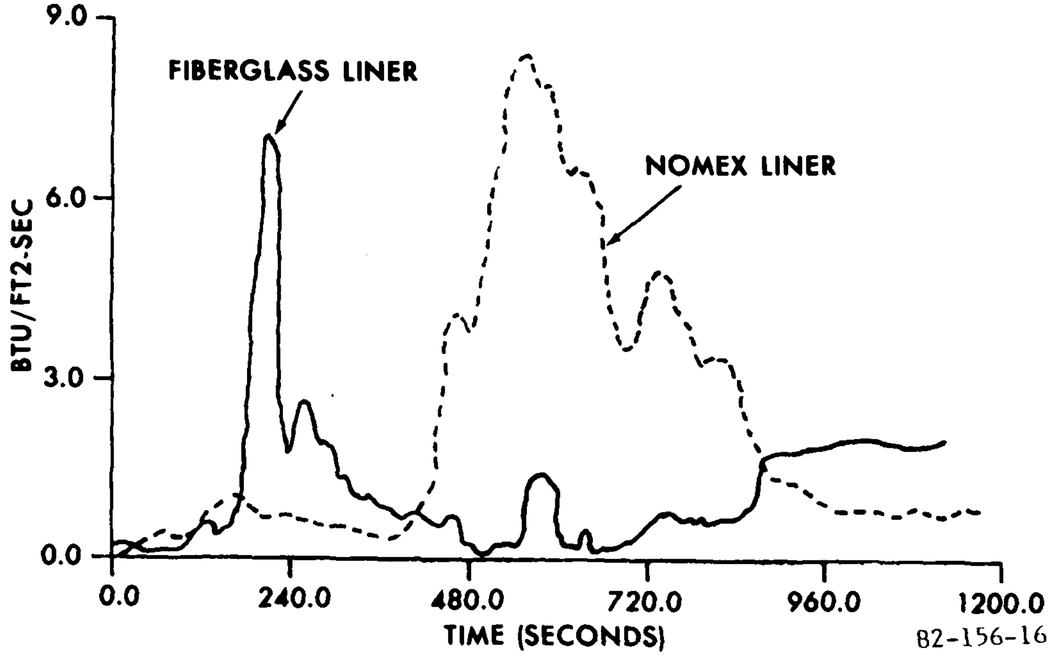

FIGURE 15. HEAT FLUX ON CEILING LINERS

TABLE 5. SMOKE DETECTOR PERFORMANCE

Test Number	Detection Time (Sec) Ceiling	Flow-Thru	Percent Light Transmission* Ceiling	Flow-Thru	Forced Air
5	536	311	80.6	90.4	No
6	210	148	85.7	92.1	Yes
8	483	386	91.3	97.5	No
9	308	264	94.4	98.3	No
10	445	432	77.6	93.5	Yes

* Percent Light Transmission over 1 foot.

Table 6 is an example of how a thermal detector would perform in a cargo compartment. A chromel-alumel thermocouple, 5 feet from the fire origin and 6 inches below the drop ceiling was used to simulate a thermal detector. The times that this thermocouple reached 150,200 and 250° F are recorded in columns 2 through 4. The time the smoke detector signaled the presence of smoke is recorded in column 5. The times in test 2 through 10 were when the recessed ceiling detector signaled. This detector was destroyed in test 10 so the flow-through detectors response time was tabulated for the remaining tests. Column 6 is the temperature on the ceiling liner directly over the fire when the reference thermocouple reached 150°. Column 7 is the temperature on the ceiling liner directly over the fire when the smoke detector lit. The smoke detector responded faster on only four of the fourteen tests. On three of those four tests, the difference in temperatures on the ceiling liner was not significant (the temperature on the ceiling liner when the smoke detector alarmed was not significantly lower than the temperature on the ceiling liner when the reference thermocouple reached 150°). In test 9 the temperature on the liner at the time of smoke detection was already high enough to damage the liner. In the majority of tests when the thermocouple responded (reached 150°) faster than the smoke detector, there was a significant difference in temperatures on the ceiling liner. The smoke detector responded faster in fires that started slowly and smoldered before breaking into open flames. The thermocouple responded (reached 150°) faster in fires that started quickly with open flame. This type of fire is much more damaging than a smoldering one and therefore more important to detect quickly. The smoke detector responded faster in eight of the fourteen tests when 200° was used as the temperature at which the thermal detector was assumed to alarm. The smoke detector was faster in ten of the fourteen tests using 250° as the reference temperature.

TABLE 6. THERMAL AND SMOKE DETECTOR DATA

Thermocouple Located 5 Feet From Fire Origin And 6 Inches Below Drop Ceiling. Time To Reach Indicated Temperature Shown In Table In Seconds.					Highest Temperature At Ceiling At t_1	Highest Temperature At Ceiling At t_4	Fire Load
	150°F	200°F	250°F	Smoke Detection			
Test	t_1	t_2	t_3	t_4	°F	°F	
2	118	158	180	179	215	520	LUGGAGE
3	290	416	475	201	510	525	
4	167	208	250	185	770	805	
5	671	*	*	536	360	330	LUGGAGE
6	145	213	281	210	275	335	
7	138	166	176	180	365	770	
8	960	*	*	483	445	305	
9	772	870	*	308	1002	732	
10	408	433	444	445	400	1000	
11	10	12	14	28	680	1260	FUEL
12	26	29	32	30	640	800	
16	251	276	288	269	545	800	ONE PIECE LUGGAGE
17	35	45	53	55	650	650	CUSHION
18	50	65	74	53	815	850	CUSHION

SUMMARY OF RESULTS

1. Nomex ceiling liners burned through in each case. Burnthrough occured 0 to 40 seconds after smoke detection.

2. The polyester resin used with the fiberglass ceiling liner was partially burned away but the glass cloth remained intact for all tests.

3. Typical cargo fires can produce maximum temperatures of 1800° F and maximum heat flux of 8.6 BTU/ft^2-sec at the ceiling liner. The peak fire conditions are only slightly lower on the upper sidewall liner when the fire is adjacent to the sidewall.

4. The recessed ceiling detector became saturated during several tests. It indicated clear air when the test article was completely filled with dense smoke.

5. A survey of class D cargo compartment liners found that most are fiberglass with the exception of the Nomex used in the C3 cargo compartment on the Lockheed L-1011.

CONCLUSIONS

1. The results of past work, along with those from this program, indicate that cargo fires can easily reach dangerous proportions in any size compartment.

2. A good fire barrier liner (i.e., fiberglass) can contain baggage fires in a 640-cubic foot class D cargo compartment.

3. Fire growth and severity is greater in a compartment with forced ventilation.

4. The cargo compartment smoke detectors evaluated did not produce any early fire warning and even when activated produced subsequent signals that gave a false indication of smoke clearing.

5. The test method specified in FAR 25.855 and FAR 25.853 do not reflect the burnthrough resistance of class D cargo liners subjected to realistic fires.

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APPENDIX A

CARGO COMPARTMENT CLASSIFICATION FAR 25.857 CLASSES A THROUGH E

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CARGO COMPARTMENT CLASSIFICATION FAR 25.857 CLASSES A THROUGH E

Class A

A class A cargo or baggage compartment is one in which (1) the presence of fire would be easily discovered by a crew member while at his station; and (2) each part of the compartment is easily accessible in-flight.

Class B

A class B cargo or baggage compartment is one in which (a) there is sufficient access in flight to enable a crew member to effectively reach any part of the compartment with the contents of a hand-held fire extinguisher; (b) when the access provisions are being used, no hazardous quantity of smoke, flame, or extinguishing agent will enter any compartment occupied by the crew and passengers; and (c) there is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

Class C

A class C cargo or baggage compartment is one not meeting the requirements for either a class A or B compartment but in which (1) there is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station; (2) there is an approved built-in fire extinguishing system controllable from the pilot or flight engineers station; (3) there are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by the crew or passengers; and (4) there are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

Class D

A class D cargo or baggage compartment is one in which (a) a fire occuring in it will be completely confined without endangering the safety of the airplane or the occupants; (b) there are means to exclude hazardous quantities of smoke, flames or other noxious gases, from any compartment occupied by the crew or passengers; (c) ventilation and drafts are controlled within each compartment so that any fire likely to occur in the compartment will not progress beyond safe limits; and (d) consideration is given to the effect of heat within the compartment on adjacent critical parts of the airplane. For compartments of 500 cubic feet or less, an airflow of 1500 cubic feet per hour is acceptable.

Class E

A class E cargo compartment is one on airplanes used only for the carriage of cargo and in which (a) there is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station; (b) there are means to shut off the ventilation airflow to or within the compartment, and the

control of these means are accessible to the flight crew in the crew compartment; (c) there are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and (d) the required crew emergency exits are accessible under any cargo loading conditions.

APPENDIX B

REPORTED INCIDENTS OF CARGO FIRES

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REPORTED INCIDENTS OF CARGO FIRES

The following are some examples of smoke or fire in cargo compartments.

August 29, 1971, a Boeing 707 made an unscheduled stop in Shannon, Ireland while en route from New York to Tel Aviv when a passenger notified the flight crew that a section of cabin flooring was hot. The plane landed safely and the passengers unloaded without incident. The AFT cargo compartment was opened and a fire in it was extinguished with water and foam. The fiberglass cargo compartment liners were charred but not burned through. The cause of the fire was undetermined but assumed to originate from the spontaneous ignition of stored chemicals. There was slight structural damage to the aircraft.

November 3, 1973, a Boeing 707 freighter crashed at Logan International Airport, Boston, after heavy smoke was reported in the cockpit while the airplane was in-flight. The airplane was destroyed and the three crew members were killed. The cause of the accident was the inability of the crew to function due to the presence of dense smoke in the cockpit that was continuously generated and uncontrollable. The National Transportation Safety Board investigation concluded that the smoke was from the exothermic chemical reaction between leaking nitric acid cargo, improperly packed and stowed, and the improperly used sawdust packing surrounding it (reference 7 of this report).

August 15, 1977, a McDonnell Douglas DC-9 stopped on a taxiway after smoke was reported. The passengers were unloaded through the forward entrance. The forward baggage bin was opened and a burning mail bag was discovered. There was no damage to the aircraft.

December 3, 1979, a Boeing 727 made an unscheduled landing after reports of smoke in the cabin and cockpit. The cabin floor was damaged to gain access to the forward cargo compartment where a burning mail bag was discovered.

January 7, 1982, a Gulfstream G159 made an unscheduled landing after a smoke detector activated and smoke was noted in the cabin. Upon landing, it was discovered that a package had fallen through the cargo net and was resting on a door light.

The following cases were reported in reference 8 of this report.

Case 1 September 1, 1979, BAC 1-11-500

"During baggage loading in the rear hold, a suitcase burst into flames. The case was removed quickly from the aircraft and the fire extinguished. The passenger owning the suitcase was identified and the contents examined in her presence. The case contained, apart from scorched underwear, six large boxes of "ship" brand matches, one box of which had ignited. After checking that the fire was completely extinguished the case was reloaded."

Case 2 December 23, 1979, BAC 1-11-500

"Whilst unloading luggage at Luton, handlers noticed a strong smell of burning. After being unintentionally hit by another case, the suitcase in question gave off billows of smoke and an acrid smell. The suitcase was removed to the fire training

ground and the passenger was brought to identify the case which was then opened. Several boxes of Italian/Spanish matches were found, one box of which had ingnited."

Case 3 August 25, 1980 BAC 1-11-500

"During baggage loading a loader noticed smoke billowing out of a suitcase he had just loaded. He quickly removed the case from the aircraft and informed the crew. A fireman opened the case and found that one of six large boxes of safety matches, loosely wrapped in a lady's personal belongings, had ignited."

The above three incidents happened to the same operator. That operator already had a restricted articles notice in small print on tickets issued. Subsequently they have increased the publicity on restricted articles.

Case 4 July 13, 1980 GATWICK BAC 1-11

"A suitcase being loaded was seen to be emitting smoke. Investigation found two packs of "swan vestas" matches (i.e., 20 boxes). One box had ignited."

Case 5 September 1980

"During the cruise a passenger reported a smell of smoke which was traced to another passenger's cabin baggage. This contained a burning box of Spanish matches which had become impregnated with Spanish brandy leaking from a bottle in the same case. The fire was rapidly extinguished by the cabin staff."

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